A HYBRID ADAPTIVE OPTICS SYSTEM FOR SPACE SITUATIONAL AWARENESS

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ABSTRACT

We are developing and will commission a space debris and object detection system in New Zealand that will provide high resolution capability to examine orbiting near Earth objects using a simplified, low-cost approach, where acquired data on new candidate objects are updated on a database. We will use a modular wide-field adaptive optics (AO) system to determine spatially variant distortion functions from multiple natural guide stars to compensate for atmospheric turbulence. To achieve this, our custom designed geometric wavefront sensor will provide estimates of phase distortion from each source object. Orbiting satellites and large space debris objects are detected within a wide field of natural stars, where a combination of closed- and open-loop adaptive optics are applied. A closed loop tip/tilt mirror system removes low-order aberrations in real-time, whereas an open-loop system will use deconvolution from wavefront sensing with batch processing to remove high-order distortion. Fast moving target objects will be imaged using a separate detector, where high frame rate-images of relatively bright objects will be used to minimise motion blur, and where synchronisation with AO cameras will allow removal of both low- and high-order aberrations from captured images. The hybrid AO system described in this paper will provide a platform to test novel methods for the detection of small, faint, fast-moving objects using alternative methods to atmospheric tomography.

1 INTRODUCTION

According to Ragazzoni [1], correction of distorted astronomical images caused by atmospheric turbulence over the entire sky, is possible. However to achieve this, significant advancements, such as new technology, instrumentation, and algorithm efficiency, are required.

The suggestion of whole sky atmospheric turbulence correction is attractive for several reasons. Firstly, our group has recently received funding for the application of an adaptive optics (AO) system which we propose to apply for space situational awareness (SSA). Our original proposal was based on an upgrade to our existing open-loop system that uses deconvolution from wavefront sensing over multiple background stars for correction [2]; this will now include an AO subsystem for tip/tilt removal resulting in a hybrid approach, which we believe will further improve the resolution of satellite images. Secondly, laser guide stars are a popular choice for many observational sites, where placement of a laser generated guide star within an isoplanatic patch can be used as a reference source for image correction [3]. However, despite the technical challenges and cost associated with developing this technology, it is doubtful our premier observatory near Lake Tekapo in New Zealand will ever be allowed to generate such a source. New Zealand has two heritage dark sky regions, one of which is the Aoraki-Mackenzie International Dark Sky Reserve and the second is Great Barrier Island. Both regions have strict regulations on light pollution of the atmosphere, and our cultural responsibilities promote stewardship of the night sky. Lastly, in 2018 New Zealand was the latest country to achieve space launch capability. As a result, New Zealand has a responsibility to develop and maintain a space situational awareness policy.

A site profile for the installation of an adaptive optics system has been conducted for the University of Canterbury Mt. John Observatory (UCMJO) [4], and the principal site characteristics are outlined in Table 1. Based on the design parameters outlined in Table 1, which addresses two wind velocity $v(h)$ profiles, a tip/tilt wavefront corrector system operating at 60 Hz is proposed.

2 SYSTEM OVERVIEW

Adaptive optics is used on ground-based telescopes to minimise the effects of atmospheric turbulence [5]. However, such technology is not only suitable for astronomical photometry, adaptations for space situational awareness are emerging. In fact, the development of AO systems to improve the quality of satellite images was commissioned by the US advanced research projects agency for surveillance of satellites from the mid-1960s [6]. Some recent developments of adaptive systems for optical telescopes in Australia include a modular system for small telescopes [7] and 1.8 m class [8] telescope for general photometry and space situational awareness applications.

Table 1: University of Canterbury Mt. John Observatory AO design parameters for $D_T = 1$ m and $v(h)$ as specified [4].

Profile Characteristic (sensor wavelength of 550 nm)	**MJUO2V**	**MJUOV3**
Fried parameter (r_o) for dominant ground layer	5.06 cm	5.06 cm
Greenwood frequency (f_G)	68 Hz (min)	81 Hz (max)
Tyler frequency (f_T)	10 Hz (min)	12 Hz (max)
Isoplanatic Angle (θ_0)	1.5 arcseconds (average)	1.1 arcseconds (pupil plane)

Currently, New Zealand does not support adaptive optics systems on any of their mid-sized telescopes (1.8, 1.0, and 0.61 m primaries) at the UCMJO. However, a proposed hybrid system outlined in this paper aims to address this.

Fundamentally, a hybrid optical correction and image restoration system is proposed, where a partially compensated tip/tilt system is combined with deconvolution from wavefront sensing (DWFS). Figure 1 shows our approach, where an aberrated image $\mathbf{g} = \mathbf{f} \odot \mathbf{h} + \eta$, where $\mathbf{f}$ is an unperturbed image of a centrally-located (within the FoV) natural star, $\mathbf{h}$ is the distortion function, and η is noise. Representing the Fourier transform of $\mathbf{g}$, a Shack Hartmann wavefront sensor forms part of the electro-optical instrumentation system, and measures aberrations in the pupil. The AO subsystem shown hosts a tip/tilt mirror and control system. Low-order Zernike estimates are used to compensate a spatially variant, long-exposure point spread function (PSF) $\mathbf{h}_{LE}$ in real-time using closed-loop control. The residual wavefront error ϵ_{R}^2 is taken and used for correction. Concomitantly, residual wavefront error is estimated using a geometric wavefront sensor [9], where a short-exposure PSF $\mathbf{h}_{SE}$ is estimated for DWFS. A wide field-of-view (WFoV) imaging system allows multiple natural beacons to be measured up to the seventh order, where atmospheric tomography [10] is proposed for reconstruction of the SVPSF.

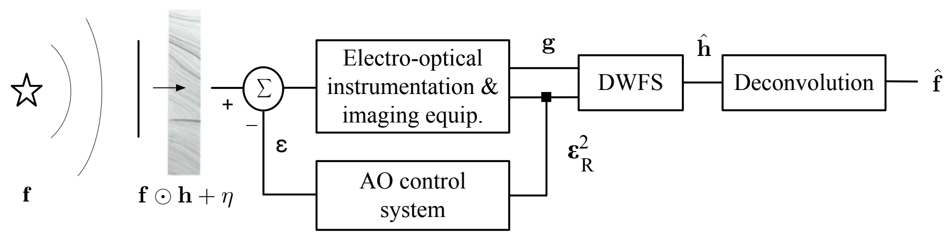

Figure 1: A partially compensated deconvolution from wavefront sensing image restoration system.

Spatially invariant estimates of $\hat{\mathbf{h}}$ have been developed using a machine learning approach [2], however, other extensions to more conventional atmospheric tomographic imaging techniques [10] are being developed. A key requirement is the development of a wide-field, multi-object wavefront sensor. Such a sensor has been successfully tested in the laboratory [11] and is discussed in Section 4.

3 NATURAL GUIDE STAR ESTIMATES FOR ATMOSPHERIC TOMOGRAPHY

Without one or more laser guide stars [3], multiple, natural guide stars will be used to estimate the SVPSF over a WFoV. For space situational awareness, reflected sunlight from spacecraft has limited use for image restoration as it is not a point source. Therefore, an estimate of the spatially variant PSF is used for image reconstruction. Assuming the hypothesis that accuracy of the SVPSF is directly proportional to the number of natural point source objects that can be measured simultaneously over a WFoV, estimating, firstly regions where star density is maximised, and secondly, estimating average densities within these regions, is a critical requirement for our research.

Stars are distributed non-uniformly over the sky because star density is higher in the galactic plane and lower in galactic poles. The brightness of a star is determined by its apparent magnitude (m), where both properties are inversely proportional. Hence, two factors are crucial for imaging multiple stars over a WFoV: (a) location of the FoV in the sky and (b) sensitivity of the image sensor to detect faint stars. Figure 2 shows the average number of stars per square degree over the galactic plane, pole, and entire sky. If the image sensor detects stars with 9th magnitude, then the average number of stars per square degree in the galactic plane, galactic pole, or entire sky is 12.8, 1.99, and 4.1, respectively [12]. Given our current FoV of 20 arcminutes, it is possible to have four stars when pointing our telescope within the galactic plane.

4 WIDE-FIELD MULTI-OBJECT WAVEFRONT SENSING

For wide-field viewing of multiple-source natural guide stars, our preferred wavefront sensor is the geometric sensor. Originally developed by van Dam [9], multi-object simulations and lab work conducted by Weddell et al. at the University of Canterbury [11] showed that in terms of accuracy and performance at low photon flux levels, the geometric sensor for adaptive optics is ideally suited for more specialised applications, such as space situational awareness.

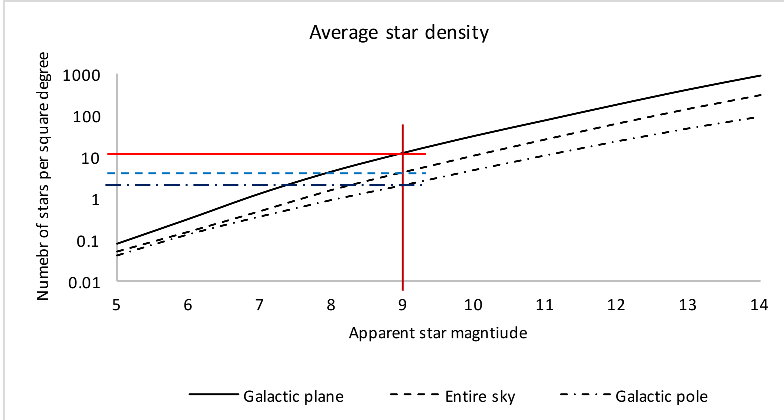

Figure 2: Average star density over the spectral band: $250 - 1050\,\mathrm{nm}$.

4.1 WFS ADAPTATION FOR ANISOPLANATIC IMAGING

To measure the SVPSF over a WFoV for space situational awareness application, a large wavefront sensor is required to measure several isoplanatic regions from multiple natural guide stars. We believe this can be achieved by imaging three or more reference stars using a geometric wavefront sensor, estimating the wavefront aberrations from each, and then use atmospheric tomography to estimate anisoplanatic regions over a wide field.

The geometric sensor, also referred to as the *twin-pupil plane* (TP-3) sensor, has been used on-sky [13, 14] for wide-field adaptive optics. Two advantages of the geometric sensor are its superior accuracy and sensitivity, compared to the curvature sensor [15]. Both sensors use two defocused planes, however the former measures wavefront slope whilst the latter measures curvature. Furthermore, it is mechanically easier to install and use than a modulated pyramid sensor. Lastly, a zonal approach is used to estimate independent sources, where Zernike modes from each zone are used to estimate the spatially variant PSF [11].

4.2 MULTI-RESOLUTION GEOMETRIC ANALYSIS

Our work has focused on adapting sparse transforms to represent optical wavefront aberrations for minimising image distortion by deconvolution. For example, using slope measurements from two defocused planes, our geometric wavefront sensor can also provide estimates of Zernike terms using ridgelets [16]. This not only reduces processing time and also improves performance over low photon flux levels, as shown in Figure 3. This is accomplished by first decomposing the image into a set of wavelet bands, and then analysing each band by a local ridgelet transform.

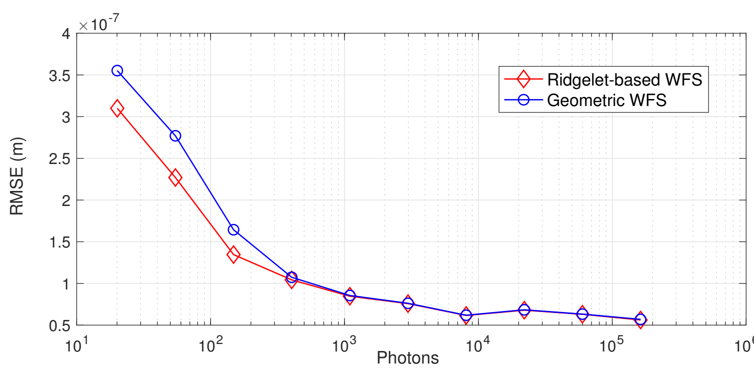

Figure 3: Comparison of the geometric wavefront sensor and ridgelet method over a range of photon flux levels [17].

5 DISCUSSION

We are currently experimenting with multi-scale and multi-directional transforms to achieve fast data processing to meet real-time requirements for atmospheric tomography. This study has provided some insight into similar, and arguably more suitable transforms. For example, we are evaluating curvelets [18] to serve as basis functions. Initial results show that curvelets may be a good candidate for representing wavefront aberrations in wavefront sensors for adaptive optics. However, many other "X-lets" exist, and mapping each variant to assess the best representation of a basis set of optical aberrations is a challenging, but hopefully rewarding process.

There are wide variances of photon flux from natural stars over a WFoV. Using FPGA control of localised substrates placed over an sCMOS sensor, better retention of phase information can be acquired. Our aim is to to firstly estimate the number, location, and magnitude of each source, and secondly, to apply spatial filtering to high flux regions of a substrate.

6 CONCLUSIONS

We have discussed in this paper a partially compensated hybrid DWFS method that we plan to use in SSA applications, such as the improvement of satellite images using ground-based telescopes. A novel, sparse geometric wavefront sensor has been developed, based on encouraging simulation results and limited on-sky results. Measuring localised phase from multiple, natural guide stars using a single wavefront sensor will form the basis of this work. We thank the Marsden Foundation of New Zealand for their support in funding this project.

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